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An analysis of solar thermal technologies integrated into a Canadian office building

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Abstract

This paper presents an analysis of three innovative solar heating and cooling systems integrated into a typical high performance office building in Montreal, Québec, Canada. A base case energy model of the office is first created in TRNSYS and used to determine the building thermal loads and the end use energy use distribution. This model then serves as the base for the analysis of several reference cases and innovative solar systems, including solar driven absorption chiller and heat pump designs. Results highlight the importance of operating the solar system in both heating and cooling modes. A combination of a GSHP with a solar driven chiller and direct solar heating was found to achieve the highest primary energy savings, with a 76% reduction relative to a standard reference system. The highest solar fractions were obtained for a solar driven absorption heat pump, with the system achieving an annual solar fraction of 0.31 while meeting nearly the entire heating load and a significant portion of the cooling load of a typical building floor through solar energy. It was concluded that the most practical application of solar energy for this building type and climate involved using solar energy to supplement a highly efficient base mechanical system such as a heat pump. Future work will examine additional climate regions and control strategies for system operations.

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Keywords: solar thermal; absorption heat pump; absorption chiller; cold climate; simulation; TRNSYS

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1. Introduction

In Canada, commercial and institutional buildings represent 12% of all secondary energy use, with 50% of this total directed towards space heating and space cooling [1]. Offices account for over 40% of the floor area in this sector [1], and thus represent a prime target for energy use reductions. With this constantly growing portion of the building stock placing an increased strain on the electrical grid, there is a growing need to reduce the energy used for heating and cooling. While extensive research has examined the importance of the building envelope in Near Zero Energy building design, relatively little attention has been given to the role of high efficiency mechanical systems in attaining this objective. This paper seeks to address this knowledge gap through a study of several innovative systems integrated into a typical office building in Montreal, Canada.

Solar thermal technologies have been recognized as having the potential to significantly reduce the energy required to heat and cool a building. However, their integration into the built environment involves overcoming several complex technical issues, including:

i. The discrepancy in time between peak solar supply and the peak building load, and;

ii. The proper application and distribution of solar energy within the building.

The potential of using solar energy, both in the residential and commercial context, has been previously examined in the literature. Argiriou et al [2] and Molero-Villar et al [3] each proposed solar heating and cooling systems integrated into residential buildings. Each study utilized a solar driven absorption chiller for cooling, while heating was provided using solar energy directly at a heating coil. Mateus and Oliveira [4] expanded on these works by performing an analysis of a solar driven absorption chiller with direct solar heating in several building types and climate regions in Europe.

In recent years there has also been growing interest in combining solar technologies with thermally driven heat pump systems. Both Nunez et al [5] and Riepl et al [6] have described heating and cooling systems where solar energy acts as a source for the generator of the thermally driven heat pump.

Each study has highlighted the importance, both from an energy and economic perspective, of extending solar system operations to include both heating and cooling. However, the vast majority of the available research has focused on warmer locations and not the harsh conditions often experienced in the cold Canadian climate. This paper aims to assess the potential of solar thermal technologies in Canada through an analysis of several innovative solar systems integrated into an office building in Montreal, Québec, Canada. An energy model of a typical office is first developed using the TRNSYS energy simulation program. This model then serves as the base for a range of mechanical systems, including both electrically and thermally driven heat pumps, and solar thermal technologies. Each system is then compared from an energy perspective in order to identify promising systems in the Canadian marketplace.

Nomenclature

COP	Coefficient of Performance (-)
CHWS	Chilled Water Supply
E	Thermal load (kWh)
F	Solar fraction (-)
G	Incident solar radiation (W/m^2°C)
GSHP	Ground Source Heat Pump
HW	Hot Water
T	Temperature (°C)
VAV	Variable Air Volume
a_0,a_1,a_2	Solar collector efficiency parameters
η	Solar collector efficiency (-)

2. Base case energy model development

An energy model of a typical office building was developed as the platform for all system analysis. The objective was to define a representative newly built office building in order to study the performance of conventional and innovative mechanical systems. Model development was based on the work described in Tamasauskas et al. [7], with the selected building having a total floor area of 14,240 m^2 spread equally across three above ground floors and a finished basement. The building was designed with a south facing orientation in order to maximize solar gains, with an aspect ratio of 1.5 and a 40% glazing fraction on each of the four facades.

In order to represent a typical new construction, the performance of the thermal envelope was based on values provided in the National Energy Code of Canada 2011 for Buildings (NECB) [8] for the Montreal climate region. Care was taken to ensure that all envelope constructions were realistic in terms of actual practice [9]. A summary of pertinent envelope performance is provided in Table 1.

Table 1.Thermal performance of building envelope.

Component	Construction Type	Thermal Performance (W/m^2K) [8]
Above Ground Walls	Insulated Mass Wall	0.247
Below Grade Walls	Insulated Concrete Wall	0.284
Roof	Metal Deck + Insulation	0.183
Slab	Insulated Concrete Slab	0.757*
Windows	Double Glazing	2.2

*For 1.2m perimeter

All lighting and receptacle loads, building occupancy and building operating characteristics were also obtained from the NECB 2011 [8].

The building had an estimated annual energy end use of 164.1 kwh/m^2 which corresponded well with available information on similar newly constructed office buildings [9].

3. Base case mechanical systems

In order to properly assess the impact of integrating solar energy into the building it was first important to quantify the performance of several reference systems. A total of three base systems were selected for analysis:

i. Conventional chiller and boiler
ii. Ground Source Heat Pump (GSHP)
iii. Indirect Fired Absorption Heat Pump

Solar thermal technologies were then implemented into these references cases with various operating strategies.

For all systems, heating and cooling for the building was based on a central plant concept: Hot and chilled water was provided by a central heating and cooling plant, and then distributed to terminal devices throughout the building. Each floor was served by a dedicated air handling unit and a VAV system, providing tempered air to each thermal zone via heating and cooling coils located inside the air handling unit. Additional heating capacity was provided using hydronic baseboards.

3.1. Fuel fired boiler with electric chiller

This case represents the most conventional method of providing heating and cooling to the building. A central fuel fired boiler was used to provide hot water to the radiators and hot water coils in the building. The boiler used in this analysis was sized for the full building heating load (445 kW), with a rated efficiency of 0.83.

Cooling was provided to the building using an electric chiller sized to meet the peak building cooling load (418 kW). The chiller unit had a rated COP of 5.6 at ARI conditions [8,10]. Heat rejection was achieved using a liquid cooling tower.

3.2. Ground source heat pump

This case examines the potential of using an electrically driven ground source heat pump system (GSHP) to meet the thermal demands of the building. During the heating season, the system was used to draw energy from the ground via a ground heat exchanger. The cycle was reversed during the cooling season, with the ground acting as a thermal sink. In order to avoid the long term effects of a net imbalance in the ground loads, a cooling tower was also implemented to reject thermal energy during the summer months.

A water to water heat pump system was selected and sized for the peak heating load (445 kW) of the building, with a rated heating COP of 3.10 and a rated cooling COP of 4.81 at AHRI ground loop rating conditions [11]. Low temperature radiators were also implemented in order to meet the heating demands of the building at the lower hot water circulation temperatures provided by the heat pump.

Appropriate sizing of the ground heat exchanger was vital for the proper operation of the system. A total of 49 single U-tube boreholes were used in the analysis, each with a depth of 83 m. A 7 x 7 borefield arrangement was selected, with a spacing of 6.1 m between each of the boreholes.

3.3. Indirect fired absorption heat pump

This system uses an indirect fired absorption heat pump system to meet the heating and cooling demands of the building. The system is thermally driven, and uses a fuel fired boiler to supply the generator side of the heat pump with hot water between 85°C to 95°C in heating and 70°C to 95°C in cooling. The basic concept of the absorption heat pump case is fundamentally similar to the electrically driven heat pump system discussed above. In heating mode, thermal energy is obtained from a low temperature source, upgraded at the heat pump, and supplied to the building. This process is reversed in the cooling season. However, instead of using a compressor to upgrade the energy, the absorption process uses a high temperature source to drive the system. This thermally driven system becomes attractive if a high temperature heat source is available and if electrical utility rates are high.

Both modes of operation require a relatively temperature-stable source/sink for the heat pump unit. For this analysis, the ground was again selected to act as the required source/sink for the heat pump, as it represented a sufficiently large and stable source of energy in comparison to other options such as the ambient air, or waste thermal energy from the building. An auxiliary cooling tower was also implemented for heat rejection during the summer months in order to balance the ground heating and cooling loads.

As with the GSHP system, the absorption heat pump was sized to meet the peak building heating load of 445 kW, with a rated heating thermal COP of 1.5 and a rated cooling thermal COP of 0.76 [12]. Although a search of the literature did not find any commercially available models, performance of this unit was obtained from available test data and used to demonstrate the potential of such a system [12]. Low temperature radiators were also implemented due to the lower hot water circulation temperatures anticipated with the absorption system.

Proper sizing of the borehole field was again critical in order for the system to operate optimally. In this case, a total of 100 boreholes (10 x 10 arrangement) were used, each with a length of 82.1 m. The required borefield size was significantly greater than for the GSHP because of the larger loads placed on the ground by the lower COP of the absorption unit in cooling mode.

4. Solar systems

Upon definition of each base case mechanical system, three distinct solar systems were examined. These systems ranged from a cooling only application to a more complex integration of solar thermal technologies with a thermally driven heat pump. In all cases, solar energy was supplied to the building via an evacuated tube solar collector array sized for the full building roof area (array area 1,166 m^2). Evacuated tube collectors were selected for this application because of their improved efficiency at the higher operating temperatures required by the absorption units. A storage tank farm with a total volume of 75 m^3 (64 l/m^2 [6]) was also implemented to bridge the gap between thermal supply and demand.

4.1. Solar driven absorption chiller

The proposed solar driven cooling system is shown in Fig. 1(a). This system is implemented into the conventional chiller/boiler reference case, with the solar driven absorption chiller operating in parallel to the electric chiller to meet a portion of the cooling load. The objective is to use smaller scale solar cooling to compliment the operation of an electric chiller, rather than completely replace it. This concept is interesting as it allows for a reduction in the building peak electrical demand during the summer months.

Solar energy obtained from the solar collectors is first stored in a storage tank farm with a temperature ranging between 70°C to 95°C. This stored energy is then used at the generator of a single effect absorption chiller sized to meet the peak cooling demand of the middle building floor. The absorption chiller does not operate if there is insufficient solar energy supplied from the storage tank farm. All additional cooling capacity is provided using an electric chiller, while a fuel fired boiler is used to meet the heating demand of the building.

The absorption chiller is sized with a capacity of 118 kW in order to supplement rather than completely replace the operation of the electric chiller. The unit has a rated thermal COP of 0.7 [13].

4.2. Solar driven absorption chiller with direct heating

This system combines a solar driven absorption chiller with direct solar heating in order to extend the operating period of the installed solar collector array. The concept is integrated into both the conventional chiller/boiler and GSHP cases to assess the impact of using solar with conventional and heat pump systems.

During the winter months, solar energy from the storage tank farm is directed towards low temperature radiators inside the building (Fig. 1(b)). In this case the storage tank farm operates with a minimum temperature of 40°C (in comparison with 70°C for the solar chiller case), allowing for improved solar collector efficiencies and increased solar gains. In the summer months the system operates in an identical manner to the solar cooling only system discussed above. If solar energy from the tank is insufficient, auxiliary mechanical equipment (either (i) chiller and boiler or (ii) a GSHP, both identical to the reference systems) is used to meet all thermal demands for the building.

As in the solar cooling only case, the absorption chiller is sized to meet the peak cooling load of the middle building floor (118 kW), with the objective to compliment rather than completely replace the electric chiller.

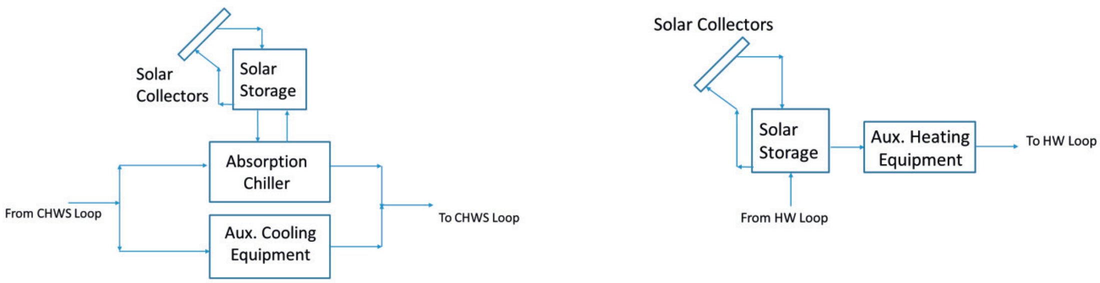

Fig. 1. (a) solar cooling integration; (b) direct solar heating integration.

4.3. Solar driven absorption heat pump

Fig. 2 shows the proposed integration of solar thermal technologies with an absorption heat pump. This concept uses solar energy to complement the operations of the indirect fired absorption heat pump, with solar energy operating in priority. Unlike the two previous solar systems, the solar driven heat pump is sized to meet the full loads of the building and acts as the primary source of heating and cooling energy. This decision was made due to the likely significant financial commitment involved with implementing such a design, including both the cost of the heat pump and borefield.

From a functional point of view, the system operates in a similar manner to the indirect fired absorption heat pump unit. Whenever possible, energy from the solar tank is used at the heat pump generator to drive operations.

Should the tank temperature drop below the defined lower limit (85°C in winter or 70°C in summer), an auxiliary boiler is used to reach the required generator temperature for operations. A series of vertical boreholes acts as the thermal source in the winter and the thermal sink in the summer, while a cooling tower is also implemented in order to balance the ground loads. A second auxiliary boiler is also implemented on the building side of the system to ensure sufficient hot water supply temperatures to the low temperature radiators.

The heat pump unit used in this case is identical to the base case and is sized for the peak heating load (445 kW). The heating and cooling COP thermal values are 1.5 and 0.76 respectively [12]. Borefield sizing is also identical to the absorption heat pump base case, with a total of 100 boreholes (each 82.1 m long) in a 10 x 10 arrangement.

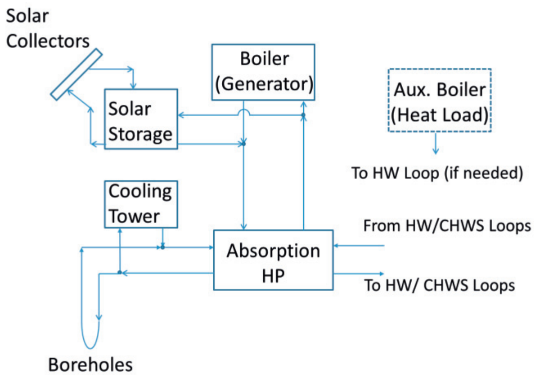

Fig. 2. solar driven absorption heat pump system.

5. Modeling approach

System analysis was performed at a time step of 7.5 minutes over a full year using a TMY2 weather file for the Montreal region. A description of the modeling approach used for major system components is provided below.

5.1. Building model

An energy model of the selected large office building was developed using the multi-zone building component in TRNSYS 17 (Type 56a) [14]. TRNSYS was selected for this application due to its strength in modeling the non-standard HVAC systems analyzed in this study. Each above ground floor was divided into a total of five zones (one core and four perimeter) in order to properly account for the diversity of loads caused by incident solar radiation. The basement floor was modeled as a single zone because of the relatively consistent boundary conditions throughout this area of the building.

5.2. Central plant

A data driven approach was used for the analysis of all major mechanical equipment within the building. Performance of the fuel fired boilers, electric chillers, and cooling tower was based on information and correlations in the NECB 2011 [8]. Performance of the absorption chiller as a function of the generator and sink temperatures was obtained from manufacturer supplied data [15]. A similar procedure was employed for the absorption heat pump based on the available literature [12].

5.3. Solar collectors

Evacuated tube collectors were selected for this application and modeled using TESS Type 538, which estimates solar collector performance using the equation:

$$\eta = a_0 - a_1 \frac{\left(T_{in,collector} - T_{ambient}\right)}{G} - a_2 \frac{\left(T_{in,collector} - T_{ambient}\right)^2}{G} \tag{1}$$

Where a_0=0.5079, a_1=0.9156 W/(m^2°C), and a_2=0.0030 W/(m^2°C^2) were obtained from the Directory of SRCC Certified Solar Collector Ratings [16].

6. Results

Systems were examined taking into account both their energy performance and their use of available solar resources. When examining thermally driven systems it is important to examine both primary and secondary energy performance. For this analysis, primary energy consumption was estimated for Québec based on information regarding the efficiency and distribution of generating capacity in the province [17] and a 4% transmission loss factor [18]. It should be noted that Quebec obtains approximately 94% of its electricity generation from hydroelectric plants, which results in poor primary energy savings. However, this analysis can easily be applied to other regions in Canada where thermal electricity production is more prevalent (i.e Alberta, Saskatchewan).

Table 2 summarizes the primary and secondary energy performance for heating and cooling of each base case. Percentage changes are referenced to the chiller and boiler case. Both heat pumps offer substantial primary and secondary energy reductions in heating mode, mainly because the heat pump is displacing a boiler with a far lower efficiency. The GSHP system demonstrates the best energy performance from both a primary and secondary energy viewpoint, with a total 64% primary energy savings. Although the absorption heat pump offers energy savings in heating mode, system operations on an annual basis result in substantial increases in primary and secondary energy use. This can be primarily attributed to the lower COP of the unit in cooling in comparison to an electric chiller. In addition, the electricity generation profile in Québec, where a significant portion of demand is met via hydroelectric plants, results in relatively high primary energy efficiency, making this option less attractive. For this region, it is clear that the system must obtain a significant portion of the generator energy input from free heat sources such as solar in order to be viable. However, this system may become more attractive in other Canadian regions where electricity is produced from thermal power plants.

Table 2. Summary of base case energy performance.

	Case		
	Chiller+Boiler	GSHP	Absorption HP
Heating Annual Energy Use (kWh eq.)	344,124	81,829 (-76%)	187,919 (-45%)
Cooling Annual Energy Use (kWh eq.)	65,276	55,336 (-15 %)	591,465 (+806%)
Total Annual Energy Use (kWh eq.)	409,400	137,165 (-66%)	779,384 (+ 90%)
Heating Primary Energy Use (kWh eq.)	344,124	88,692 (-74%)	187,919 (-45%)
Cooling Primary Energy Use (kWh eq.)	70,750	59,977 (-15%)	591,465 (+736 %)
Total Primary Energy Use (kWh eq.)	414,874	148,668 (-64%)	779,384 (+88 %)

Table 3 shows the energy performance for heating and cooling of each solar system. Percentage changes are referenced to the chiller and boiler base case. Operating the system in both heating and cooling modes offers large total energy use savings, as highlighted by the significant primary and secondary energy use reductions obtained with the direct heating and solar cooling systems. Year-round use of the solar collectors also allows the building owner to make more effective use of the installed equipment and obtain an improved return on investment.

Table 3. Summary of solar system energy performance.

	Case			
	Solar Chiller	Solar Chiller + Direct Heating	Solar Chiller + Direct Heating + GSHP	Solar Absorption HP with Ground Loop
Heating Annual Energy Use (kWh eq.)	344,124 (0 %)	240,294 (-30 %)	49,994 (-85%)	133,667 (-61%)
Cooling Annual Energy Use (kWh eq.)	58,030 (-11 %)	57,984 (-11%)	43,675 (-33%)	459,138 (+603%)
Total Annual Energy Use (kWh eq.)	402,154 (-2%)	298,278 (-27%)	93,669 (-77%)	592,806 (+45%)
Heating Primary Energy Use (kWh eq.)	344,124 (0%)	240,294 (-30%)	54,187 (-84%)	133,667 (-61%)
Cooling Primary Energy Use (kWh eq.)	62,897(-11%)	62,847 (-11%)	47,337 (-33%)	459,138 (+549%)
Total Primary Energy Use (kWh eq.)	407,021 (-2%)	303,141 (-27%)	101,525 (-76%)	592,806 (+43%)

A summary of the energy savings achieved by implementing solar thermal technologies is provided in Table 4, with systems compared against their respective base cases. The integration of solar thermal into the building has a clear impact, with annual primary energy savings between 24% and 32% for systems providing both heating and cooling.

Table 4. Summary of solar thermal energy savings.

	Case			
	Solar Chiller	Solar Chiller + Direct Heating	Solar Chiller + Direct Heating + GSHP	Solar Absorption HP
Reference Case	Chiller/Boiler	Chiller/Boiler	GSHP	Absorption HP
Heating Annual Energy Use Savings	0%	30%	39%	29%
Cooling Annual Energy Use Savings	11%	11%	21%	22%
Total Annual Energy Use Savings	2%	27%	32%	24%
Heating Primary Energy Use Savings	0%	30%	39%	29%
Cooling Primary Energy Use Savings	11%	11%	21%	22%
Total Primary Energy Use Savings	2%	27%	32%	24%

The combination of a GSHP with direct solar heating and a solar driven absorption chiller results in the most substantial reductions in primary and secondary energy use, with this system obtaining a total 76% primary energy reduction relative to a reference chiller and boiler case. This option essentially combines the most efficient reference system with a relatively straightforward integration of solar energy: The addition of solar energy to the already efficient GSHP results in an additional 39% reduction in primary heating energy and a 21% reduction in primary cooling energy.

The solar absorption heat pump offers significant energy use reductions in heating mode, as the unit is able to operate with a COP above 1 throughout the heating season. However, while the addition of solar energy helps to reduce the primary energy use of the absorption heat pump by 24%, the poor performance of the unit in cooling mode still results in a system that uses more energy annually than the reference case from both a primary and secondary energy perspective.

Each solar system was also analyzed in terms of its calculated solar fraction. For this paper, the solar fraction was calculated in terms of the percentage of the building loads met through solar energy:

$$F_{solar} = \frac{E_{Solar}}{E_{Building}} \tag{2}$$

Table 5 shows the seasonal and annual solar fractions for each system, both at the building level and for a middle building floor. While annual building solar fractions do not exceed 0.31, an examination at the floor level shows that both solar systems operating in heating and cooling are able to meet nearly the entire heating load, and a significant portion of the cooling load. This highlights the importance of having an appropriate ratio of collector area to floor space in order to achieve high solar fractions. The highest solar fractions are obtained for the solar absorption heat pump system, which can be attributed to the higher COP in heating mode, and the fact that the system is sized to meet a larger portion of the building loads in comparison to the other two solar systems. Solar fractions are lowest for the solar cooling only option, which again highlights the importance of utilizing the solar system both in heating and cooling modes to achieve optimal annual performance.

Table 5. Summary of solar fractions.

	Case		
	Solar Chiller	Solar Chiller + Direct Heating*	Solar Absorption HP with Ground Loop
Heating Season Solar Fraction Mid. Floor (-)	0.00	1.00	1.00
Heating Season Solar Fraction Building (-)	0.00	0.30	0.40
Cooling Season Solar Fraction Mid. Floor (-)	0.67	0.68	0.72
Cooling Season Solar Fraction Building (-)	0.22	0.22	0.23
Annual Solar Fraction Mid. Floor (-)	0.45	0.96	1.00
Annual Solar Fraction Building (-)	0.12	0.25	0.31

*Results representative for system in combination with chiller + boiler, or GSHP

Selection of the appropriate solar system is highly dependent on which performance metrics are most valued. From the perspective of solar energy utilization, the solar absorption heat pump appears to be the most attractive option. However, using this as the sole metric fails to take into account the substantially higher primary and secondary energy use of the system, as well as the larger capital costs associated with the installation of additional geothermal boreholes. While using a GSHP in combination with direct solar heating and an absorption chiller achieves a slightly lower solar fraction, this system demonstrates superior energy performance from a primary and secondary use perspective. Additionally, the capital costs of the system are likely to be lower due to the smaller number of boreholes required in this design. It can be concluded that for this case study that the optimal use of solar energy is as a supplement to a highly efficient base mechanical system such as a heat pump.

7. Conclusions and future work

A series of solar systems have been examined as integrated into a high performance office building in Montreal, Quebec, Canada. First, a detailed building model was created using the TRNSYS energy simulation program. This model then served as the base for the examination of several reference case and solar thermal systems, including both electrically and thermally driven heat pump technologies. Systems were then analyzed in terms of their energy performance and solar fractions in order to identify the most attractive options.

Simulated results highlighted the benefit of operating the solar system in both heating and cooling modes. From the perspective of solar energy utilization, a solar driven absorption heat pump was found to be the preferred option, with an annual building solar fraction of 0.31. However, this option also involved increased energy inputs into the system due to a lower cooling COP, and higher capital costs associated with the use of a larger geothermal borefield. A combination of a GSHP with direct solar heating in the winter and a solar driven absorption chiller in the summer is most likely to achieve the best balance of solar utilization, energy savings, and capital costs, with this system obtaining an annual building solar fraction of 0.25 while reducing primary building energy use by 76% in comparison to the fuel fired boiler and electric chiller case. In general, it can be concluded that the best application of solar energy for the combination of building and climate involves using solar energy to supplement an already efficient base mechanical system such as a heat pump.

The results of this study represent an initial examination of solar thermal systems integrated into a typical Canadian office. Future work will first examine the potential of using these systems in other regions throughout Canada, particularly those with electricity generation profiles and rate structures that would make thermally driven systems more attractive. In addition, a systematic techno-economic analysis methodology will be employed to more fully account for the financial aspects and implications of each system. Finally, at the system level, additional work will be done on the sizing and control strategies used for each system, and, in particular, the potential of using a smaller scale solar drive absorption heat pump in combination with electrically driven ground-source or air-source heat pumps. The possible use of ejector technology with the heat pump will also be explored.

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